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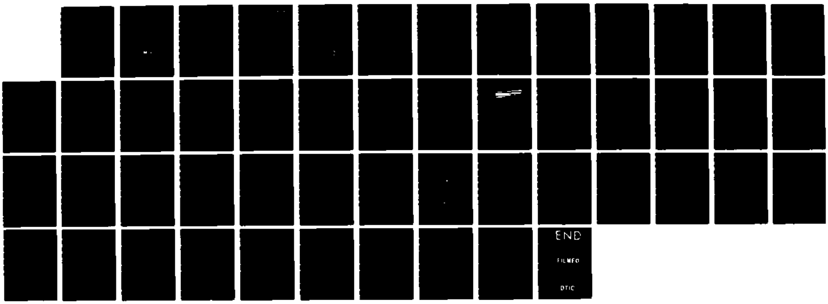

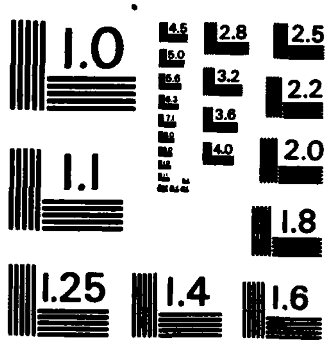

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Potential for Recoverable Coalbed Methane Resources on Navy Lands

by
Steven C. Bjornstad
Public Works Department

JUNE 1985

NAVAL WEAPONS CENTER
CHINA LAKE, CA 93555-6001

Naval Weapons Center

FOREWORD

This report documents the results of a study that was funded by the Naval Civil Engineering Laboratory, Port Hueneme, Calif., to assess the potential for recoverable coalbed methane resources at U.S. naval facilities in the United States. The study was performed during the period August 1984 through MAR. 1985 by personnel of the Geothermal Utilization Division, Naval Weapons Center, China Lake, Calif.

This report was reviewed for technical accuracy by Carl F. Austin and Allan Katzenstein of the Geothermal Utilization Division.

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(U) *Potential for Recoverable Coalbed Methane Resources on Navy Lands*, by Steven C. Bjornstad. China Lake, Calif., Naval Weapons Center, June 1985, 44 pp. (NWC TP 6626, publication UNCLASSIFIED.)

(U) This report documents a literature search that was aimed at identifying the potential for recoverable coalbed methane resources at naval facilities in the United States.

(U) Several geologic factors that influence the occurrence of coalbed methane were examined, the most important of which is coal rank. Other factors include the formation pressure, the permeability and porosity of the coal, the degree of fracturing (deformational history), the depth of burial, the distance to the outcrop, and the permeability of adjacent strata.

(U) The evaluation of the potential of any natural resource requires the development of a working model to keep in perspective the many factors affecting the occurrence of that resource. Models based on major tectonic environments were used in evaluating all naval facilities in the United States for their coalbed methane potential. While none of the sites was found to be in a primary target area for the occurrence of coalbed methane, several Navy sites were identified as having some potential. However, assessing that potential, determining the quality of the resource and the applicablility of the resource to the individual facility, as well as answering the questions of resource ownership and the resource disposition, will take a great deal more effort.

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Figures (Contd.):

Tables:

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The author wishes to express his appreciation to the librarian at the U.S. Bureau of Mines Research Laboratory, Salt Lake City, Utah, and to Craig Rightmire of the TRW Energy Development Group, Houston, Texas, for making much of the coalbed methane research data readily available to me. Thanks also to James Allen, Lt., JAGC, USNR, Head Geothermal Law, Geothermal Utilization Division, for his input on the Legal/Institutional Factors Section.

SUMMARY

In response to the energy industry's growing interest in coal as a source of natural gas and the U.S. Navy's continued awareness of the value of alternate "unconventional" energy sources, the Naval Weapons Center (NWC) has been tasked to conduct a literature search aimed at identifying the potential for coalbed methane resources at naval facilities in the United States.

To do this, it was necessary first to define what coalbed methane is. Coalbed methane will be defined as any naturally occurring gas that is present in or is intimately associated with coalbeds and has methane as its major component. This gas may be adsorbed on the micropores of the structure of the coal, present in the fractures within the coal itself, or trapped in other sedimentary units that are interbedded with the coal.

Several geologic factors that influence the occurrence of coalbed methane were examined, the most important of which is coal rank. Other factors include the formation pressure, the permeability and porosity of the coal, the degree of fracturing (deformational history), the depth of burial, the distance to the outcrop, and the permeability of adjacent strata.

The evaluation of the potential of any natural resource requires the development of a working model to keep in perspective the many factors affecting the occurrence of that resource. Usable models for the occurrence of coal (and, therefore, coalbed methane), can be developed within the framework of regional geology and global tectonics because these factors place definite limits on the accumulation of plant debris from which coal will later form (hereafter referred to as coal deposition), as well as influencing the subsequent rank of the coal, the coal's preservation potential, and the methane retention potential.

These models were used in evaluating all naval facilities in the United States for their coalbed methane potential. While none of the sites was found to be in a primary target area for the occurrence of coalbed methane (as defined by the parameters developed here and in several U.S. Department of Energy coalbed methane studies), 27 facilities at 12 sites were identified as having some potential.

Because of the limitations of time and available information, this study has concentrated on the regional geologic environment of each site. It does not address anything of a non-geologic, site-specific nature. Facility size, energy requirements,

present energy source, adaptability of this energy source to facility needs, and the like, are not addressed. The topic of the legal disposition of the resource is discussed only in general terms because there is as of the date of this report litigation ongoing between the coal mining industry and the oil and gas industry concerning the question of resource ownership.

As stated, a limited potential does appear to exist at several Navy sites, but assessing that potential will take a great deal more effort. Should the Navy wish to pursue further the potential of this alternate energy source, a site-by-site evaluation strategy is recommended. The strategy outlined is for the Bremerton Naval Facilities in western Washington, but the general format will be the same for each site.

INTRODUCTION

Historically, coal mine operators were the only people interested in coalbed methane because of the hazards associated with its occurrence in the mines. Much of the industrial and governmental effort over the past 50 years has been aimed at increasing mine safety and efficiency by developing techniques to mitigate these hazards by ventilating the working areas to reduce the concentration of methane in the air and to degasify the coal ahead of the working face by using both horizontal holes drilled in the working face and vertical holes drilled into the coal seam from the surface. Most of the gas was, and still is, vented to the atmosphere—as much as 250 million cubic feet/day (MMcf/d) by some estimates.

Within the last 10 years, along with the general increased awareness of alternative energy sources, interest has been building to use as much as possible of this wasted gas, either locally at the mine or by introducing it into pipelines for commercial distribution. Efforts have also been directed toward tapping the methane resources in coals outside the mine areas, both for commercial distribution and for use by local consumers.

Over the past few years, several companies involved in coalbed methane research and development have given briefings to Navy personnel indicating that some naval facilities may be located over coalbeds that could possibly produce methane from wells drilled into the coalbeds. In response, NWC was tasked to conduct a survey aimed at identifying naval facilities having the potential for coalbed methane resources.

To accomplish this task, a literature search was conducted to collect data on coal geology and coalbed methane technology. These data, coupled with an understanding of the regional geology around each facility, were then used to make a geologic evaluation of the site potential.

Table 1 is a complete listing of all Navy sites initially included in this survey. Those sites that were closely scrutinized are given in the section titled Site Listings. A map of the continental United States showing the major coal occurrences is included as Figure 1.

It is appropriate at this stage to point out that while this report deals strictly with Navy sites, a cursory comparison of a map of the major Army, Navy, and Air Force installations in the United States (Reference 1) and a map of the coalfields in the United States from the *1984 Keystone Coal Industry Manual* (Reference 2) indicates over 30 Army or Air Force installations that appear to lie within or adjacent to major coal basins. Therefore, the definitions and ideas developed here should apply equally well to several other military sites.

TABLE 1. Listing of U.S. Navy and Marine Corps Sites Evaluated for Coalbed Methane Potential.

Academy, Annapolis, MD
Accounting and Finance Center, Arlington, VA
Aerospace and Regional Medical Center, Pensacola, FL
Air Development Center, Warminster, PA
Air Engineering Center, Lakehurst, NJ
Air Facility, El Centro, CA
Air Facility Andrews AFB, Camp Springs, MD
Air Facility Detroit, Mt Clemens, MI
Air Propulsion Center, Trenton, NJ
Air Rework Facility, Alameda, CA
Air Rework Facility, Cherry Point, NC
Air Rework Facility, Jacksonville, FL
Air Rework Facility, Norfolk, VA
Air Rework Facility, North Island, San Diego, CA
Air Rework Facility, Pensacola, FL
Air Station, Alameda, CA
Air Station Atlanta, Marietta, GA
Air Station, Barbers Point, HI
Air Station, Brunswick, ME
Air Station, Cecil Field, FL
Air Station, Chase Field, Beeville, TX
Air Station, Corpus Christi, TX
Air Station, Dallas, TX
Air Station, Fallon, NV
Air Station, Glenview, IL
Air Station, Jacksonville, FL
Air Station, Key West, FL
Air Station, Kingsville, TX
Air Station, Lemoore, CA
Air Station Memphis, Millington, TN
Air Station, Meridian, MS
Air Station Miramar, San Diego, CA
Air Station, Moffett Field, CA
Air Station, New Orleans, LA
Air Station, Norfolk, VA
Air Station North Island, San Diego, CA
Air Station Oceana, Virginia Beach, VA
Air Station, Patuxent River, MD
Air Station, Pensacola, FL
Air Station, Point Mugu, CA
Air Station, South Weymouth, MA
Air Station Whidbey Island, Oak Harbor, WA
Air Station Whiting Field, Milton, FL
Air Station, Willow Grove, PA
Air Systems Command Headquarters Arlington, VA
Air Technical Training Center, Millington, TN
Air Test Center, Patuxent River, MD
Amphibious Base Coronado, San Diego, CA
Amphibious Base Little Creek, Norfolk, VA
Audiovisual Center, Washington, DC
Aviation Engineering Service Unit, Philadelphia, PA
Aviation Logistics Center, Patuxent River, MD
Aviation Supply Office, Philadelphia, PA
Avionics Center, Indianapolis, IN
Base Charleston, SC
Base Norfolk, VA
Base Philadephia, PA
Base San Diego, CA
Base Seattle, WA
Bureau of Medicine and Surgery, Washington, DC
Chief of Naval Education & Training, Pensacola, FL
Chief of Naval Material Arlington, VA
Chief of Naval Reserve New Orleans, LA
Civilian Personnel Command, Arlington, VA

TABLE 1. (Contd.)

Coastal Systems Center, Panama City, FL
Commander in Chief, U. S. Atlantic Fleet, Norfolk, VA
Commander in Chief, U. S. Pacific Fleet, Pearl Harbor, HI
Communication Area Master Station Atlantic, Norfolk, VA
Communication Area Master Station, EASTPAC, Wahiawa, HI
Communication Station, San Diego, CA
Communication Station, Stockton, CA
Communication Unit Cutler, East Machias, ME
Communication Unit Washington, Cheltenham, MD
Construction Battalion Center, Davisville, RI
Construction Battalion Center, Gulfport, MS
Construction Battalion Center, Port Hueneme, CA

Data Automation Command, Navy Yard, Washington, DC

Education and Training Center, Newport, RI
Education Training Program Development Center Pensacola, FL
Electronic Systems Command Headquarters, Arlington, VA
Electronic Systems Engineering Center, San Diego, CA

Facilities Engineering Command Atlantic Division, Norfolk, VA
Facilities Engineering Command Chesapeake Division, Washington, DC
Facilities Engineering Command Headquarters, Alexandria, VA
Facilities Engineering Command Northern Division, Philadelphia, PA
Facilities Engineering Command Pacific Division, Pearl Harbor, HI
Facilities Engineering Command Southern Division, Charleston, SC
Facilities Engineering Command Western Division, San Bruno, CA
Facility, Adak, AK
Facility, Barbers Point, HI
Facility Cape Hatteras, Buxton, NC
Facility Centerville Beach, Ferndale, CA
Facility Coos Head, Charleston, OR
Facility, Pacific Beach, WA
Facility Point Sur, Big Sur, CA
Facility San Nicolas Island, Point Mugu, CA
Finance Center, Cleveland, OH
Fleet Accounting & Disbursing Center, U.S. Atlantic Fleet, Norfolk, VA
Fleet Anti-Submarine Warfare Training Center Pacific, San Diego, CA
Fleet Ballistic Missile Submarine Training Center, Charleston, SC
Fleet Combat Training Center Atlantic, Dam Neck, Virginia Beach, VA
Fleet Combat Training Center Pacific, San Diego, CA
Fleet Material Support Office, Mechanicsburg, PA
Fleet Training Center, Mayport, FL
Fleet Training Center, Norfolk, VA
Fleet Training Center, San Diego, CA
Fuel Depot, Jacksonville, FL

Guided Missile School Dam Neck, Virginia Beach, VA

Hospital, Beaufort, SC
Hospital, Cherry Point, NC

Intelligence Command Headquarters, Suitland, MD
Intelligence Support Center Suitland, MD

Magazine, Lualualei, HI
Marine Barracks, Washington, DC
Marine Corps Air Facility, Quantico, VA
Marine Corps Air-Ground Combat Center, Twentynine Palms, CA
Marine Corps Air Station, Beaufort, SC
Marine Corps Air Station, Cherry Point, NC
Marine Corps Air Station El Toro, Santa Ana, CA
Marine Corps Air Station Kaneohe Bay, Oahu Island, HI
Marine Corps Air Station, Yuma, AZ
Marine Corps Air Station (Helicopter) New River, Jacksonville, NC
Marine Corps Air Station (Helicopter) Tustin, CA
Marine Corps Base, Camp Lejeune, NC
Marine Corps Base, Camp Pendleton, CA
Marine Corps Camp Elmore, Norfolk, VA
Marine Corps Camp H. M. Smith, Halawa Heights, HI
Marine Corps Development and Education Command, Quantico, VA
Marine Corps Finance Center, Kansas City, MO
Marine Corps Headquarters, Arlington, VA
Marine Corps Logistics Base, Albany, GA
Marine Corps Logistics Base, Barstow, CA
Marine Corps Recruit Depot, Parris Island, SC

TABLE 1. (Contd.)

Marine Corps Recruit Depot, San Diego, CA
Military Personnel Command Arlington, VA
Military Sealift Command Atlantic, Bayonne, NJ
Military Sealift Command Pacific, Oakland, CA
Military Sealift Command, Washington, DC
National Naval Medical Center, Bethesda, MD
Naval District Washington Headquarters, Washington, DC
Nuclear Power Training Unit, Ballston Spa, NY
Nuclear Power Training Unit, Idaho Falls, ID
Nuclear Power Training Unit, Windsor, CT
Observatory Flagstaff Station, Flagstaff, AZ
Observatory (Naval), Washington, DC
Ocean Systems Center, San Diego, CA
Oceanography Command, NSTL Station, MS
Ordnance Station, Indian Head, MD
Ordnance Station, Louisville, KY
Pacific Missile Range Facility, Barking Sands, Kekaha, Kauai, HI
Pacific Missile Test Center, Point Mugu, CA
Polaris Missile Facility Atlantic, Charleston, SC
Postgraduate School, Monterey, CA
Public Works Center, Great Lakes, IL
Public Works Center, Norfolk, VA
Public Works Center, Pearl Harbor, HI
Public Works Center, Pensacola, FL
Public Works Center, San Diego, CA
Public Works Center San Francisco Bay, Oakland, CA
Publication and Forms Center, Philadelphia, PA
Radio Station Jim Creek, Oso, WA
Radio Station, Sugar Grove, WV
Recruit Training Command, Great Lakes, IL
Recruit Training Command, Orlando, FL
Recruit Training Command, San Diego, CA
Regional Medical Center, Bremerton, WA
Regional Medical Center, Camp Lejeune, NC
Regional Medical Center, Camp Pendleton, CA
Regional Medical Center, Charleston, SC
Regional Medical Center, Corpus Christi, TX
Regional Medical Center, Great Lakes, IL
Regional Medical Center, Jacksonville, FL
Regional Medical Center, Long Beach, CA
Regional Medical Center Memphis, Millington, TN
Regional Medical Center, Newport, RI
Regional Medical Center, Oakland, CA
Regional Medical Center, Orlando, FL
Regional Medical Center, Philadelphia, PA
Regional Medical Center, Portsmouth, VA
Regional Medical Center, San Diego, CA
Research Laboratory, Washington, DC
Sea Systems Command Headquarters, Arlington, VA
Security Group Activity, Adak, AK
Security Group Activity, Homestead, FL
Security Group Activity Northwest, Chesapeake, VA
Security Group Activity Skaggs Island, Sonoma, CA
Security Group Activity, Winter Harbor, ME
Security Group Command Headquarters, Washington, DC
Security Station, Washington, DC
Service School Command, Great Lakes, IL
Service School Command, Orlando, FL
Service School Command, San Diego, CA
Ship Research and Development Center Annapolis Lab, Annapolis, MD
Ship Research and Development Center Carderock Lab, Bethesda, MD
Ship Weapon Systems Engineering Station, Port Hueneme, CA
Ships Parts Control Center, Mechanicsburg, PA
Shipyard, Charleston, SC
Shipyard, Long Beach, CA
Shipyard Mare Island, Vallejo, CA
Shipyard Norfolk, Portsmouth, VA
Shipyard, Pearl Harbor, HI
Shipyard, Philadelphia, PA
Shipyard Portsmouth, Kittery, ME
Shipyard Puget Sound, Bremerton, WA
Station, Adak, AK
Station, Annapolis, MD
Station, Charleston, SC
Station, Long Beach, CA
Station, Mayport, FL
Station New York, Brooklyn, NY
Station, Norfolk, VA
Station, Pearl Harbor, HI
Station, Philadelphia, PA
Station, San Diego, CA
Station Treasure Island, San Francisco, CA
Strategic Weapons Facility Pacific, Bremerton, WA

TABLE 1. (Contd.)

Submarine Base, Bangor, WA Submarine Base New London, Groton, CT Submarine Base Pearl Harbor, HI Submarine Medical Center New London, Groton, CT Submarine School New London, Groton, CT Submarine Support Base, Kings Bay, GA Submarine Support Facility New London, Groton, CT Submarine Support Facility, San Diego, CA Supply Annex Cheatham, Williamsburg, VA Supply Center, Charleston, SC Supply Center, Norfolk, VA Supply Center, Oakland, CA Supply Center, Pearl Harbor, HI Supply Center, Puget Sound, Bremerton, WA Supply Center, San Diego, CA Supply Corps School, Athens, GA Supply Systems Command Headquarters, Arlington, VA Support Activity, New Orleans, LA Support Activity, Seattle, WA Surface Weapons Center, Dahlgren, VA Surface Weapons Center, White Oak Laboratory, Silver Spring, MD	Technical Training Center, Corry Station, Pensacola, FL Telecommunications Command Headquarters, Washington, DC Training Center, Great Lakes, IL Training Center, Orlando, FL Training Center, San Diego, CA Training Equipment Center, Orlando, FL Undersea Warfare Engineering Station, Keyport, WA Underwater Systems Center, Newport, RI War College (Naval), Newport, RI Weapons Center, China Lake, CA Weapons Engineering Support Activity, Washington, DC Weapons Station, Charleston, SC Weapons Station, Concord, CA Weapons Station, Colts Neck, Earle, NJ Weapons Station, Seal Beach, CA Weapons Station, Yorktown, VA Weapons Support Center, Crane, IN

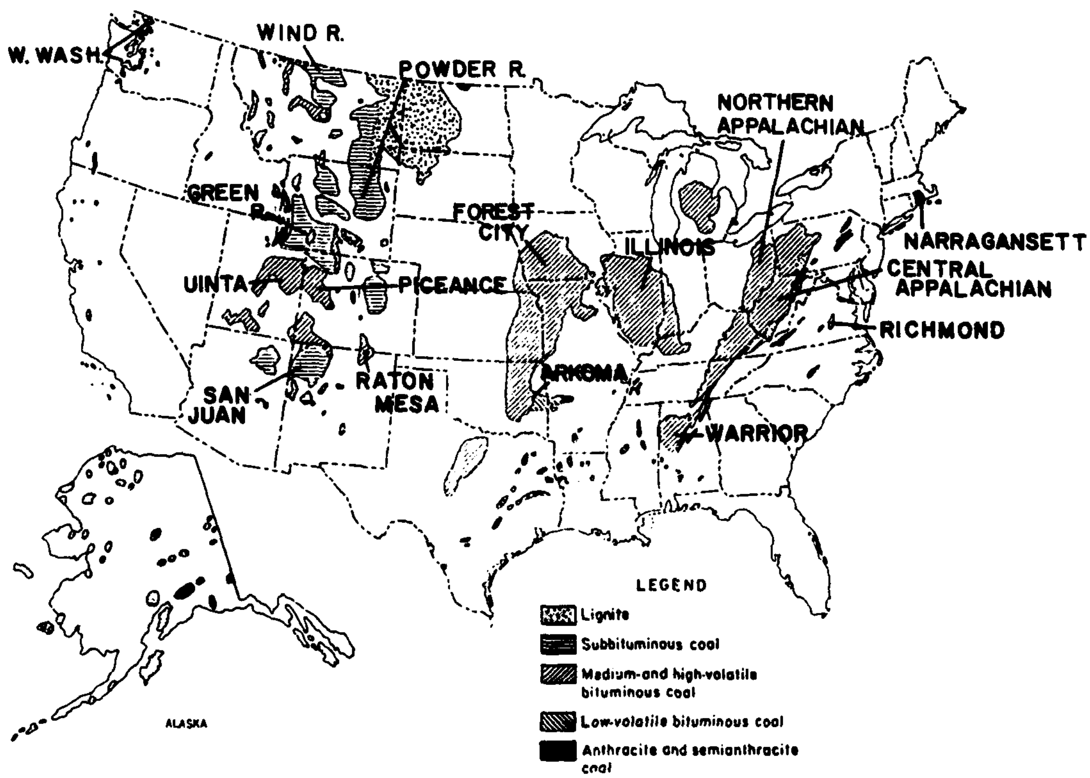

FIGURE 1. Major Coal Occurrences in the United States.

DEFINITION OF COAL AND COALBED METHANE TERMS

To understand what a coalbed methane resource is, we must first define a number of related terms. The first set of terms concern the host rock and the second set relate to the resource itself.

1. What is coal and what is a coalbed?

2. What is natural gas/methane and what is coalbed gas/coalbed methane?

The American Geological Institute *Glossary of Geology* (Reference 3) defines coal as

> . . . a readily combustible rock containing more than 50% by weight and more than 70% by volume of carbonaceous material including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat. Differences in the kinds of plant materials (type), in degree of metamorphism (rank), and in the range of impurity (grade) are characteristics of coal and are used in classification.

This definition is consistent with those from other sources. *A Dictionary of Mining, Mineral, and Related Terms* (Reference 4) states further that coal is

> . . . more or less distinctly stratified (and) varies in color from dark brown to black . . .

The dictionary goes on to state that

> The boundary line between peat and coal is hazy. . . as is the boundary line between coal and graphite and the boundary line between carbonaceous rock and coal.

Such a statement would indicate that the minimum characteristics of 50% by weight and 70% by volume of carbonaceous matter are probably a guideline rather than a strict standard.

By using a tetrahedron to show the composition of sediments and sedimentary rocks (as developed by Pettijohn (References 5 and 6)) it is possible to represent graphically the natural transformation between coal and the other sedimentary rocks. Figure 2, adapted from Reference 6, shows one of the fundamental tetrahedrons with organic matter as an end member. (The other tetrahedron is identical except that chert (microcrystalline quartz) is substituted for organic matter.) In this tetrahedron, the quartz vertex represents sandstone, the clay vertex represents shale, the carbonate vertex represents limestone, and the organic matter vertex represents coal and bitumen. (Bitumens are the naturally occurring flammable substances of an oily nature. Petroleums, asphalts, and natural waxes are considered bitumens.)

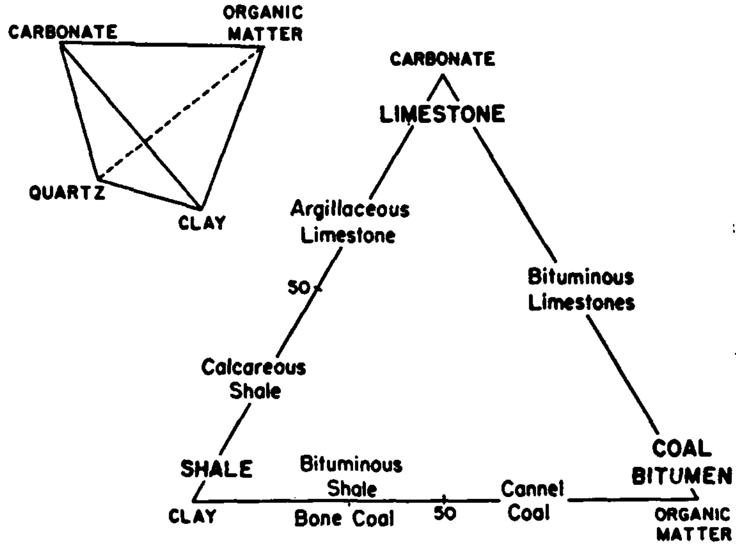

FIGURE 2. A Fundamental Sedimentary Classification Tetrahedron and the Clay, Carbonate, Organic-Matter Face Shown in Detail.

Also represented in Figure 2 is a detail of the carbonate, clay, and organic-matter face of the tetrahedron showing some of the transitional units between the end members. The definition of each unit is not distinct because there is an unbroken transition from one end member to the next. A complete range exists from slightly organic to highly organic sediments, for example.

For the purpose of this study, we will define coal as a readily combustible, more or less distinctly stratified rock, generally containing more than 50% by weight and more than 70% by volume of carbonaceous material including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat (coalification), and dark brown to black in color. This definition of coal should effectively separate it from other sedimentary and metamorphic rocks containing carbonaceous matter.

The definition of coal does not include peat. While being an early stage in the metamorphism of plant matter into coal, peat is the product of biogenic, partial decomposition and disintegration of plant remains, in the absence of air, in marshlands where the moisture content of the peat is over 90% (Reference 7). Coal, on the other hand, is formed by diagenetic alteration rather than a biogenic process and its formation is dependent primarily on temperature and time and secondarily on pressure. Diagenetic alteration refers to all the chemical or physical changes that the plant matter undergoes after the biogenic process ceases.

Coal is ranked into four classes. In increasing calorific value and decreasing percentage of volatile matter, these are lignitic, subbituminous, bituminous, and anthracitic (Table 2). The process of coalification transforms original plant material into these progressively higher ranks of coal. Coalification begins as a biogenic process

with the reduction of plant debris to peat. Carbon dioxide (CO_2) and methane (CH_4) are the predominant gasses produced. A typical analysis of the gas contained in peat shows 97% CO_2 and 3% CH_4 (Reference 8). At this point, the depth of burial and increasing temperature kills off the microorganisms in the peat and the diagenic process takes over. Methane is formed during this process from both the organic material and most of the carbon dioxide, although CO_2 can occur in amounts up to 15% in some coals (Reference 9). The high-volatile A to low-volatile bituminous coals are considered to be the gassiest coal ranks.

TABLE 2. Classification of Coal by Rank.

Group	Fixed carbon limits, % (dry, mineral-matter-free basis)		Volatile matter limits, % (dry, mineral-matter-free basis)		Calorific value, Btu/lb (moist, mineral-matter-free basis)	
	Equal to or greater than	Less than	Greater than	Equal to or less than	Equal to or greater than	Less than
Class I. Anthracitic						
Meta-anthracite	98	...	...	2	...	...
Anthracite	92	98	2	8	...	...
Semianthracite	86	92	8	14	...	...
Class II. Bituminous						
Low-volatile bituminous coal	78	86	14	22	...	...
Medium-volatile bituminous coal	69	78	22	31[a]	...	...
High-volatile A bituminous coal	...	69	31	...	14000	...
High-volatile B bituminous coal	...	...	...	...	13000	14000
High-volatile C bituminous coal	...	...	...	...	11500	13000
Class III. Subbituminous						
Subbituminous A coal	...	...	...	...	10500	11500
Subbituminous B coal	...	...	...	...	9500	10500
Subbituminous C coal	...	...	...	...	8300	9500
Class IV. Lignitic						
Lignite A	...	...	...	...	6300	8300
Lignite B	...	...	...	...	...	6300

[a] Increased CH_4 yield at ≈29% volatile matter.

A coalbed has been defined in Reference 4 as

> . . . a bed or stratum of coal. (The term) coal seam is more commonly used in the *United States* and Canada.

In a stratified sequence of rocks, a coalbed is interspersed with and distinguishable from other sedimentary rock units above and below it. The other units are commonly sandstones, shales, clays, limestones, and various mixtures thereof. Coalbeds range from a fraction of an inch (called horizon markers) to over 100 feet thick.

The definition of coalbed can become somewhat clouded when the coalbed is interbedded in the stratigraphic column with other sedimentary units that are unusually rich in plant debris, such as carbonaceous shales, sandstones, and dolostones, because there is sometimes a vertical grading from one unit to the next. This vertical gradation is usually only a matter of a few inches thick. The majority of the coals we will be concerned with are at least several inches thick so that the boundary between the coal and the adjacent rock unit is readily distinguishable.

Two major environments of deposition existed for the plant material that became coal. The first were extensive, low-elevation swamps, lagoons, and river delta regions as exist in the southeastern United States today. This environment accounts for the extensive coal deposits of Carboniferous age in the eastern United States, most of the Cretaceous coal-bearing units of the Rocky Mountain region, and the lignites of south Texas. The second type of environment is related to more tectonically active areas and upland river regions where the river deltas are small and the swamps are more correctly termed bogs or marshlands and cover much smaller areas. The coal deposits of the western United States and the smaller deposits associated with the extensive coal occurrences would be of this type.

The second set of terms that need to be defined are natural gas/methane and coalbed gas/coalbed methane. This combination of terms expands into several more readily definable terms: natural gas, methane, firedamp, marsh gas, coal gas, gas from coalbeds, and coalbed methane. From these definitions, we should be able to arrive at an understanding of the term coalbed methane as it will be used in this study.

Levorsen, in his text, *Geology of Petroleum* (Reference 10) defines natural gas as

> . . . a petroleum that is a gaseous mixture under surface conditions of temperature and pressure but some of which becomes liquid underground with higher temperature and pressure. Natural gas consists predominantly of paraffin hydrocarbons, chiefly methane and varying but generally small amounts of the heavier paraffins.

The *McGraw-Hill Encyclopedia of Energy* (Reference 11) is somewhat more detailed by stating that

> The generic term natural gas applies to gases commonly associated with petroliferous geologic formations. As ordinarily found, these gases are combustible, but nonflammable components such as carbon dioxide, nitrogen, and helium are often present. Natural gas is generally high in methane. . . . There is no single composition which might be termed typical natural gas. . . . The net heating value of natural gas served by a utility company is often 1,000 to 1,100 Btu/cu. ft. . . .*

The compositions of some typical natural gases from oil or gas wells and in pipelines are given in Tables 3 and 4, which were adapted from Reference 7.

TABLE 3. Typical Natural Gases From Wells.

Composition, mole %						
Gas	Origin of sample					
	La.	Miss.	N. Mex.	Okla.	Tex.	W. Va.
Methane	92.1	96.3	67.7	63.2	43.6	96.9
Ethane	3.8	0.1	5.6	3.1	18.3	1.7
Propane	1.0	0.0	3.1	1.7	14.2	0.3
Normal butane	0.3	0.0	1.5	0.5	8.6	0.1
Isobutane	0.3	0.0	1.2	0.4	2.3	0.0
Normal pentane	0.1	0.0	0.6	0.4	2.7	0.3
Isopentane	Trace	0.0	0.4	0.2	3.3	0.0
Cyclopentane	Trace	0.0	0.2	Trace	0.9	Trace
Hexanes plus	0.2	0.0	0.7	0.1	2.0	0.1
Nitrogen	0.9	1.0	17.4	27.9	3.0	0.6
Oxygen	0.2	0.0	Trace	0.1	0.5	Trace
Argon	Trace	Trace	0.1	0.1	Trace	0.0
Hydrogen	0.0	0.2	0.0	0.0	0.1	0.0
Carbon dioxide	1.1	2.3	0.1	0.4	0.5	0.0
Helium	Trace	Trace	1.4	2.1	Trace	Trace
Heating value [a]	1062	978	1044	788	1899	1041

[a] Calculated total Btu/cu. ft. at 60°F and 30 in. Hg. Btu/cu. ft. = British thermal units per cubic foot of gas.

*Btu/cu. ft. = British thermal units per cubic foot of gas.

TABLE 4. Typical Natural Gas in Pipelines.

Composition, mole %					
Gas	Origin of sample				
	Colo.	Kan.	Kan.	Okla.	Tex.
Methane	94.3	72.3	88.9	75.4	85.6
Ethane	2.1	5.9	6.3	6.4	7.8
Propane	0.4	2.7	1.8	3.6	1.4
Normal butane	0.2	0.3	0.2	1.0	0.0
Isobutane	0.0	0.2	0.1	0.6	0.1
Normal pentane	Trace	Trace	0.0	0.1	0.0
Isopentane	Trace	0.2	Trace	0.2	0.1
Cyclopentane	Trace	0.0	Trace	Trace	0.0
Hexanes plus	Trace	Trace	Trace	0.1	Trace
Nitrogen	0.0	17.8	2.2	12.0	4.7
Oxygen	Trace	Trace	Trace	Trace	Trace
Argon	0.0	Trace	0.0	Trace	Trace
Hydrogen	Trace	0.1	0.1	0.0	0.0
Carbon dioxide	2.8	0.1	0.1	0.1	0.2
Helium	Trace	0.4	0.1	0.4	0.1
Heating value[a]	1010	934	1071	1044	1051

[a]Calculated total Btu/cu. ft. at 60°F and 30 in. Hg.

Methane is defined in a straightforward manner by the American Geological Institute *Glossary of Geology* (Reference 3). It states that methane is

> A colorless, odorless inflammable gas, the simplest paraffin hydrocarbon, formula CH_4. It is the principal constituent of natural gas and is also found associated with crude oil.

The definition stated in A *Dictionary of Mining, Mineral, and Related Terms* (Reference 4) reflects the mining orientation of this reference book. It defines methane as

> CH_4, carbureted hydrogen or marsh gas or firedamp; formed by the decomposition of organic matter. The most common gas found in coal mines. It is a tasteless, colorless, nonpoisonous, and odorless gas; . . . often referred to as firedamp because it is the principal gas composing a mixture which when combined with proper proportions of air will explode when ignited.

As can be seen, in some cases the environment in which the methane is found will determine what it is called. For example, firedamp is a combustible gas that contains chiefly methane, and is formed in mines by the decomposition of coal or other carbonaceous matter; while marsh gas is methane produced during the decay of plant matter in stagnant water (as during the formation of peat).

Coal gas has been defined in Reference 3 as

> The fuel gas produced from gas coal; its average composition, by volume, is 50% hydrogen, 30% methane, 8% carbon monoxide, 4% other hydrocarbons, and 8% carbon dioxide, nitrogen, and oxygen.

This production process is the gasification, either in a surface gasification plant or *in situ*, of gas coal (bituminous coal) that contains 33 to 38% volatile matter. This definition would not include gas that exists naturally in the coal. Some confusion is apparent in the literature, however, because a *Dictionary of Mining, Mineral, and Related Terms* (Reference 4) defines coal gas as

> Flammable gas derived from coal either naturally or by induced methods of industrial plants and underground gasification.

This definition would include all hydrocarbon-containing gases whether they are manufactured or naturally evolved from coal.

Naturally occurring gas from the majority of coalbeds is of considerably different composition than is gas from a gasification process. Table 5 shows the average composition of gas from several coalbeds.

While these are accepted average compositions for gas encountered in the major coal fields, the composition of naturally occurring coal gas is more variable than indicated, especially in the smaller or younger coal seams. For example, an analysis of thirteen samples from nine different wells drilled into the relatively young coal-bearing formations in northwest Washington State showed nitrogen concentrations ranging from 2.5 to 70% and averaging 33.2% (Reference 12).

Another definition of gas from coalbeds is available from the National Gas Policy Act (NGPA) of 1978 (Public Law 95-621). The NGPA was intended to provide for new price and contract regulations, make emergency provisions for natural gas supplies, and set forth curtailment policies regarding the production and supply of natural gas in the United States. It established a series of maximum prices for several categories of gas. In the NGPA, gas from coal seams is defined as a "high cost" gas because it is more expensive to produce than is conventional natural gas.

TABLE 5. Average Composition of Gas From Coalbeds, %.

Gas	Coalbed name and location						
	Pocahontas No. 3, Va.	Pittsburgh, Pa. & W.Va.	Upper Kittanning, Pa.	B Seam, Colo.	Lower Hartshorne, Okla.	Mary Lee, Ala.	Anthracite, Pa.
Methane	94.9	91.1	97.4	87.8	99.2	96.0	98.7
Ethane	1.3	0.3	0.01	0.05	0.01	0.01	0.1
Propane	0.004	...[a]	...[a]	0.005	...[a]	...[a]	Trace
Butane	0.002	...[a]	...[a]	0.001	...[a]	...[a]	...[a]
Pentane	Trace	...[a]	...[a]	...[a]	...[a]	...[a]	...[a]
Carbon dioxide	0.3	8.2	0.1	12.0	0.1	0.1	0.1
Oxygen	0.2	0.2	0.2	...[a]	0.1	0.1	...[a]
Nitrogen	3.2	0.5	2.3	0.1	0.6	3.5	1.0
Hydrogen	0.02	...[a]	...[a]	...[a]	...[a]	Trace	...[a]
Helium	0.04	...[a]	...[a]	...[a]	...[a]	0.3	Trace
Btu/scf[b]	1030	975	1037	935	1056	1022	1053

[a] Not detected.
[b] British thermal unit per standard cubic foot.

With the above definitions of various "gas" terms in hand, we should be able to arrive at an acceptable definition of coalbed methane.

For the purpose of this study, coalbed methane will refer to any naturally occurring gas that is present in or is intimately associated with coalbeds and has methane as its major component. Coalbed methane will be considered synonymous with coalbed gas. This gas may be adsorbed on the micropores of the structure of the coal, present in the fractures within the coal itself, or trapped in other sedimentary units that are interbedded with the coal. In some cases, because of the generally thin nature of the bedded units and their intimate association, it may be difficult or impossible to distinguish the specific coal units for production purposes. In addition, in view of the results of numerous coalbed gas drainage tests (References 13 through 17), it appears to be technologically impractical to attempt to produce gas from individual coal seams of less than 3/4 foot in thickness without also exposing the units above and below the seam. Figure 3 shows an example of a set of thin, interbedded units.

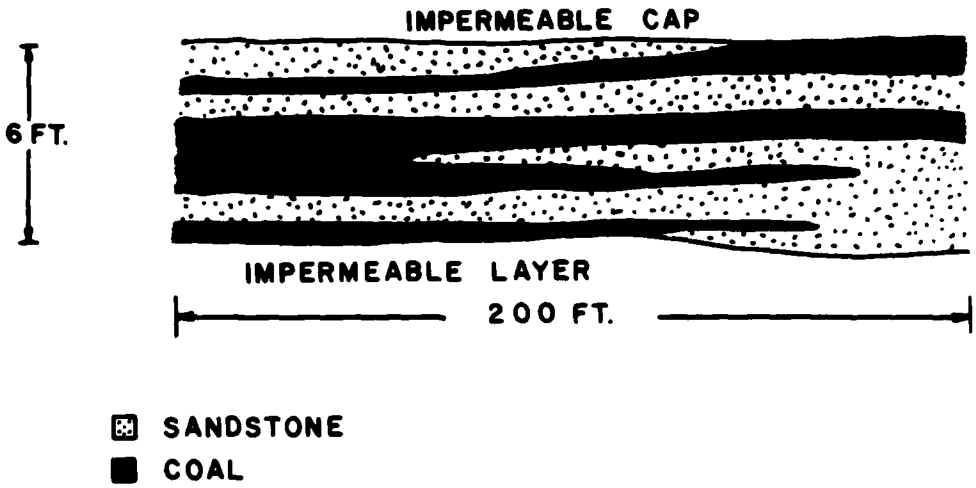

FIGURE 3. Example of Thin Coalbeds Interbedded With Thin, Permeable Sandstone Units.

FACTORS THAT INFLUENCE THE OCCURRENCE OF COALBED METHANE

Methane is produced throughout the coalification process. As stated earlier, the amount of methane produced is dependent on temperature and time because temperature determines the rate at which coalification proceeds and time (duration of heating) influences the final (or present) rank of the coal. Experimental data have shown that there is a sharp increase in the rate of methane formation when the percentage of volatile matter in the coal reaches approximately 29%, which falls into the category of medium-volatile bituminous coal (Reference 8). Measured gas content values in coals range from 0.032 to 704 cubic feet/ton (cf/T). Table 6 shows the range in gas content and rank for coals from several major coal basins (References 12 and 18). Caution must be used in reference to these and other published figures of gas content or large areas because the figures are often based on limited data.

While the high-volatile A bituminous to low-volatile bituminous coals are, on average, the gassiest, coals of the same rank may exhibit a 10,000-fold difference in gas content. This difference is an indication that the present gas content of a coalbed is related not only to gas formation during coalification but to all the factors that are part of the postdepositional history of the coalbed.

TABLE 6. Gas Content and Rank of Coals From Several Major Coal Basins.

Basin	Gas content, cf/T	Coal rank
Arkoma	200-450	Bituminous
Black Warrior	7.5-600	Bituminous to semianthracitic
Green River	10-540	Subbituminous to bituminous
Illinois	40-150	Bituminous
No. Appalachians	33-429	Bituminous
Piceance	1-339	Lignitic to anthracitic
Powder River	15-100	Lignitic to subbituminous
Raton Mesa	25-490	Bituminous to anthracitic
San Juan	10-135	Subbituminous to bituminous
W. Washington	65-440	Subbituminous to anthracitic

The gas content of a coalbed depends not only on coal rank but also on the formation pressure, the permeability and porosity of the coal, the degree of fracturing (deformational history), the depth of burial, the distance to the outcrop, and the permeability of adjacent strata. Each of these factors is intimately related to one or more of the others.

Unlike most oil and gas reservoirs, coalbeds are both the source rock and the reservoir for the gas. Because of the low permeability of coal, most of the gas stays where it was formed. In an undisturbed coalbed, most of the methane is adsorbed on the coal within the extensive micropore structure of the coal and only a small percentage of the methane is found as "free" gas in the fractures. The transport of the methane from the micropores is governed by concentration gradients (gas partial pressures); and overburden, hydrologic, and deformational pressures. For example, the removal of water from a coalbed (either at the mining face underground or by way of vertical surface drill holes) creates a pressure drop at that point and a pressure gradient from the formation toward that point. Adsorbed methane will tend to desorb from the micropores and flow through the natural or induced fracture system in the rock down the pressure gradient. As long as this disequilibrium gradient is maintained, desorption will continue. The same is true for the formation of natural fractures in the coal, but the overburden and hydrologic pressures tend to prevent the pressure gradient—that results from the fracturing—from being very great or from being maintained very long so that the amount of gas desorbed is probably not very great.

As with nearly all consolidated rock formations, most coal is extensively fractured. These fractures are referred to as cleats in the coal mining industry; and, while pervasive, they usually are not well interconnected. In some coalfields, primarily in the southeastern United States, the coal seams have to be artificially fractured to provide an avenue large enough for the economic removal of the desorbed gas.

The closer a particular site underlain by coal is to that coal's outcrop, the lesser are the overburden and hydrologic pressures on the coal. Fracturing tends to be more pronounced, and gas loss is greater.

The permeability and other lithologic characteristics of strata adjacent to, and especially above, a coalbed are important because the strata can act as barriers or conduits to the movement of gas out of the coalbed.

As stated, temperature and time affect coal rank and, therefore, gas content. The effects of temperature overshadow the effects of time, so that the age of the coal is a significant factor in the relative amount of gas contained in a coalbed only in areas that have not been subjected to higher-than-normal heat flows.

On average, coals of the same rank will increase in gas content as depth of burial increases. This is most likely a function of formation and hydrologic pressures.

As a point of reference, a bituminous coal that contains 400 cf/T gas will contain 705,000 cubic feet/acre-foot (Mcf/Af) of coal seam, so that a 5-foot-thick coal seam will contain about 3.5 million cubic feet per acre (MMcf/A). Estimates of recovery percentages vary from 40 to 75%+ depending on the reference cited. Recovery estimates are evolved from a small data base and will not be reliable until a fair number of fields are produced and the factors that affect recovery are better understood.

COALBED METHANE OCCURRENCE MODELS

Usable modes for the occurrence of coal (and, therefore, coalbed methane), can be developed within the framework of regional geology and global tectonics because these factors place definite limits on the accumulation of plant debris from which coal will later form (hereafter referred to as coal deposition). These factors also influence the subsequent rank of the coal, the coal's preservation potential, and the methane-retention potential. An in-depth discussion of tectonic settings and their relationship to coal and other mineral deposits is given by Mitchell and Garson (Reference 19) and is beyond the scope of this study. A brief introduction to the subject is necessary, however, to demonstrate that the wide spectrum of coal deposits that exist are the result of a variety of tectonic processes. This introduction will be accomplished by describing the tectonic settings of the major coal occurrences in the continental United States. Figure 4, modified from Reference 19, shows these various tectonic environments and how they occur in relation to one another.

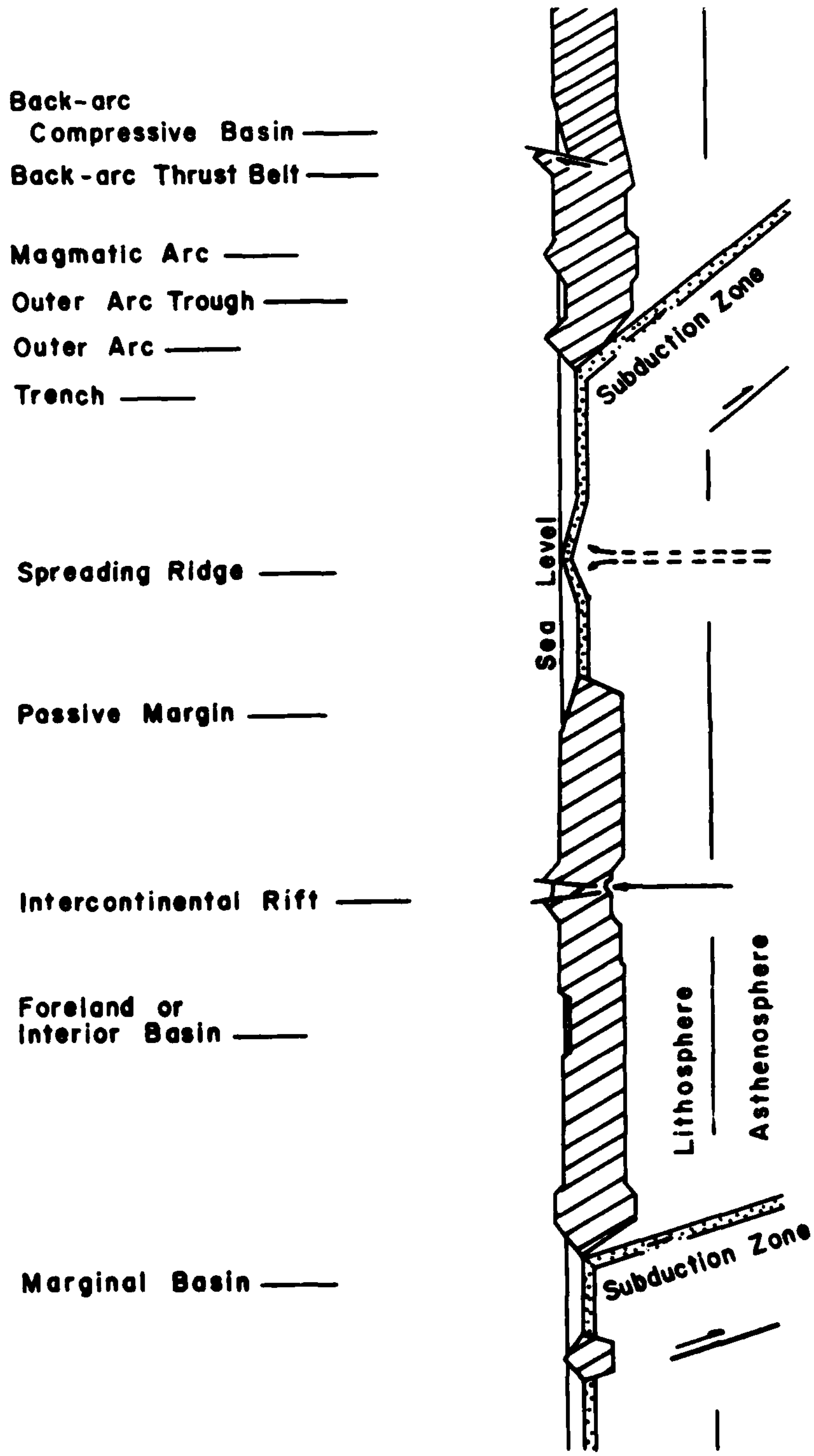

FIGURE 4. Diagrammatic Illustration of Several Tectonic Settings. (Not to scale.)

The majority of the coal deposits in the eastern United States, as well as most of the coals on the European continent, were deposited during the Carboniferous Period (350 to 275 million years ago (Ma)) in two major tectonic settings. The Upper Carboniferous successions of the Southern Appalachian and Black Warrior Basins are good examples of coal deposition in a foreland basin. Foreland basins border the continental or inland side of a foreland thrust belt on the subducting continental plate and are often major sedimentary basins. The Upper Carboniferous coals of the rest of the Appalachians (and of Northern Europe) are associated with river deltas formed on the passive margin of a second continent. A passive margin setting is characterized by continued subsidence throughout the history of the adjacent ocean floor. This activity results in an extensive, thick sedimentary section. The rank of the coal in both settings is primarily dependent on their depth of burial within the thick sedimentary section, their age, and in this instance, the heat generated by the later collision of these two continents.

A second, more minor period of coal deposition occurred in the Triassic Period (225 to 180 Ma). Small basins formed in the Atlantic Coastal region from North Carolina to Rhode Island, probably in an intercontinental rift setting that occurred in this area just prior to the opening of the Atlantic Ocean in the Jurassic Period.

The next major accumulation of coal in the North American continent occurred primarily in the Cretaceous Period (135 to 65 Ma), although sedimentation and coal accumulation continued well into the Tertiary Period (up to 12 Ma). This deposition occurred in a series of basins in the west-central United States. These are the Piceance, Uinta, San Juan, Wind River, Greater Green River, Powder River, and Raton Mesa Basins. Collectively, this area is called a back-arc compressive basin because it lies landward of the active margin settings (magmatic arc, back-arc thrust belt, and the like). The back-arc basin supports widespread sedimentation, especially large deltas, and because of its position in the continental interior, it is likely to be preserved until a major continental collision occurs.

As with other tectonic settings, the rank of coals deposited in a back-arc compressive basin are dependent on postdepositional changes of the tectonic environment. The Rocky Mountain region of British Columbia and Alberta, Canada, provides an excellent example of coals deposited in a back-arc compressive basin and the relationship of coal rank to regional tectonics.

In the Rocky Mountain coal belt, coal deposits are confined to the Upper Jurassic to Lower Cretaceous Kootenay Formation, deposited to the east of the back-arc thrust belt. The Rocky Mountain coals, highly deformed in the Laramide Orogeny when the thrust belt migrated eastward, are low- and medium-volatile bituminous coals and anthracites. To the east in the less deformed Foothills region are lower rank high-volatile bituminous coals, while farther east in the Plains region are subbituminous coals and lignites (Reference 19).

Additional examples of the effects of postdepositional tectonics are available from the central United States. In the San Juan Basin the coals range in rank from subbituminous A to high-volatile B bituminous except in the northern part of the basin where higher rank, medium-volatile bituminous coals were formed under the influence of the San Juan Mountains intrusive heat source. In the Raton Mesa Basin, the coalification process has been accelerated by heat generated through the formation of the Rio Grande Rift in the early Tertiary.

The third major era of coal deposition occurred in the Early to Middle Tertiary (65 to 25 Ma), which includes the major deposits of western Washington as well as many minor occurrences, such as those in the Great Valley sequence in California and in the Coastal Range in southern Oregon (Reference 2). These deposits occur in active tectonic settings, such as outer-arc troughs and marginal basins. Each of these depositional sites develops in a subduction zone-transform fault setting as seen in Figure 4. An outer-arc trough lies between an outer-arc and a volcanic-plutonic arc; and a marginal basin lies at the subduction zone. In each of these settings, the preservation potential of any coal deposited is not very great because the settings are at an active continental margin and are usually destroyed during continental collision. This is probably the reason that all the deposits that have been identified as being associated with these settings are young.

The rank of coals found in the subduction zone settings is variable, and this variability sometimes occurs within a relatively short distance. For example, in the Great Basin of California the coals have remained largely lignitic. In the western Washington region, however, the Tertiary sediments have been subjected to heat from the Cascade volcanic-plutonic arc, resulting in coals that range from subbituminous to anthracitic in a distance of less than 4 miles.

Major accumulations of coal, in the form of lignite, occurred in this same time frame in the southern United States (Texas, Louisiana, Mississippi, Alabama, and Arkansas) (Reference 20). The Gulf of Mexico has been the site of sediment deposition since the late Jurassic (140 Ma), and the area is considered to be an ocean basin because the thick sediment accumulation is ultimately underlain by oceanic crust. This area is classed as a passive margin setting although it is affected by forces related to both the Caribbean and western Mexico subduction zones. As stated above, the preservation potential for coals deposited in a passive margin setting is good; but because such a setting is a relatively inactive area tectonically, the rank of coals found here is dependent on the age of the sediments and their depth of burial.

From the above discussion, it should be apparent that the potential for the occurrence of a given type of coal deposit in a given region of the United States is strongly dependent on the tectonic history of that region. This is especially true of

the large deposits. Because the Pacific Coast region of the United States lies in a very active tectonic setting, the potential for the occurrence of an extensive or thick coalbed is very slight.

The potential for preservation of coalbed methane is also dependent on the tectonic setting, but is primarily related to subsequent changes to the original setting rather than to the original depositional environment. In addition to coal rank effects, igneous or metamorphic activity in a tectonically active area can cause extensive fracturing of a coalbed, allowing the gas to escape. Because of this, one would expect coals in a collision margin setting, for example, to contain less than coals of the same rank in a passive setting.

SITE LISTING

The following discussion includes only those Navy sites initially identified during the literature search as having possible coalbed methane potential. These sites are discussed in greater or lesser detail according to their considered potential. Sites have been grouped together as dictated by their similar geology, geographic setting, or resource potential. Table 7 is a listing of these sites by state. Figure 5 is a map of the continental United States showing the Navy sites and their relationship to the major coal basins.

INDIANA

The Crane Weapons Support Center is located in Martin County, Indiana, which is underlain by the Raccoon Creek Group of coal-bearing sedimentary strata on the eastern side of the Illinois Basin. The Illinois Basin is thought to have been a passive interior basin formed on continental crust inland from the passive margin of the northern Appalachians.

Stratigraphically, the Raccoon Creek Group includes (from bottom to top) the Mansfield, Brazil, and Stauton formations of lower Pennsylvanian age (320 to 300 Ma). These strata dip gently to the west. Only coals of the Mansfield Formation are mapped or identified in Martin County (Reference 2). The upper formations outcrop to the west. The coals are ranked high-volatile C bituminous but have an unusually low methane content of 30 to 150 cf/T, as do all coals in the Illinois Basin (Reference 12). Because of the gentle dip of these strata and the fact that at least some of the Mansfield coals outcrop on the Weapons Support Center, the potential for substantial coalbed methane resources at this site is not great. A small resource may be present under the western side of the facility if the coalbeds are buried.

TABLE 7. Navy Sites Initially Considered To Have Coalbed Methane.

Map Site, Fig. 5	Location	Base or Facility
	Indiana	
1	Crane	Weapons Support Center
	Missouri	
2	Kansas City	Marine Corps Finance Center
	Mississippi	
3	Meridian	Air Station
	Tennessee	
4	Memphis	Regional Medical Center Air Technical Training Center Air Station, Millington
	Washington	
5	Bremerton	Regional Medical Center Puget Sound Shipyard and Supply Center Submarine Base, Bangor
5	Keyport	Undersea Warfare Engineering Station
6	Seattle	Support Activities Base
7	Oak Harbor	Whidbey Island Air Station
8	Oso	Jim Creek Radio Station
	Oregon	
9	Charleston	Coos Head Facility
	California	
10	Vallejo	Mare Island Shipyard
10	Concord	Weapons Station
10	San Francisco	Treasure Island Station
10	Alameda	Air Rework Facility
10	Oakland	Public Works Center Regional Medical Center Supply Center Military Sealift Command Pacific
11	Monterey	Postgraduate School
	Rhode Island	
12	Davisville	Construction Battalion Center
12	Newport	Regional Medical Center Underwater Systems Center War College

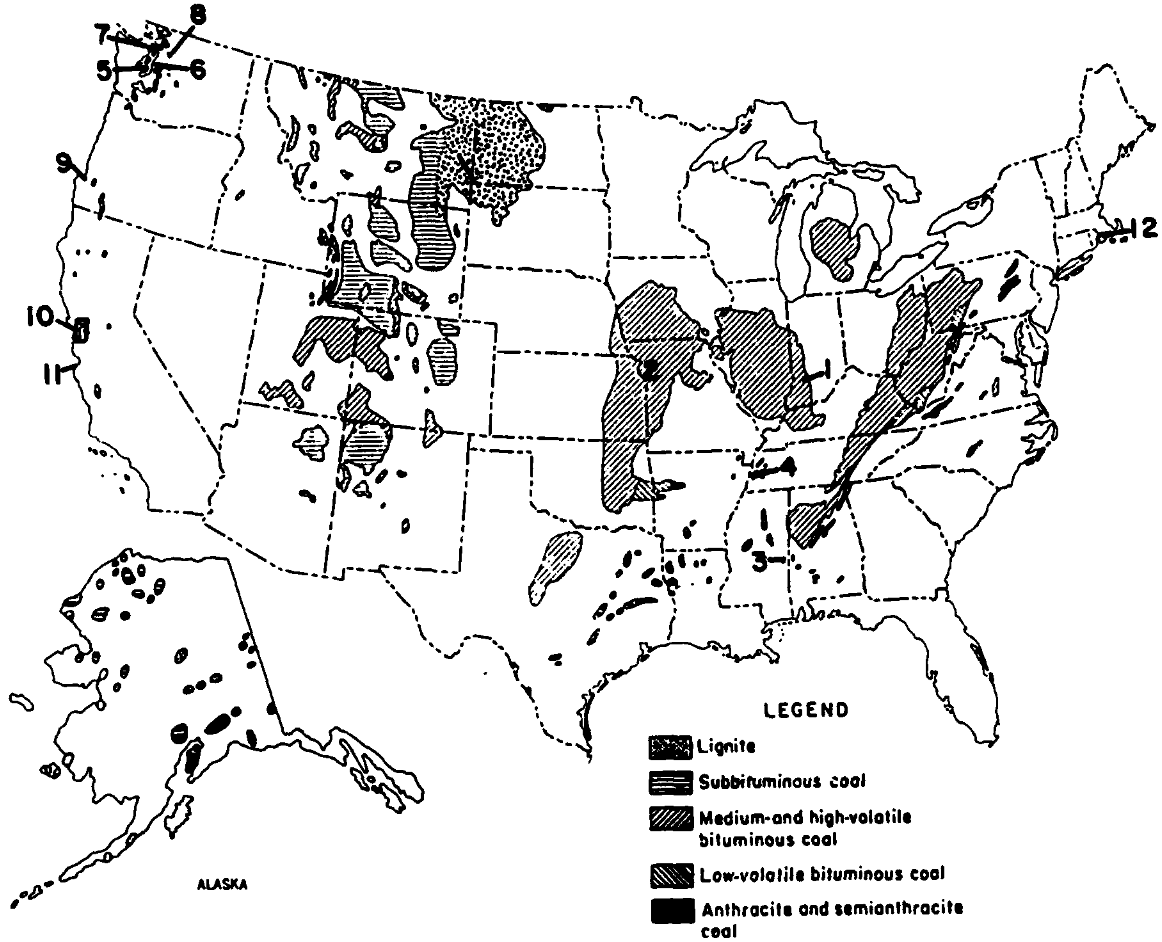

FIGURE 5. Location Map Showing the Relationship of the Navy Sites With Possible Coalbed Methane Potential and the Major Coal Occurrences in the United States.

MISSOURI

Kansas City, Missouri, lies in the south-central part of the Forest City Basin, which, like the Illinois Basin, is a passive interior basin, and the coals deposited in it are Pennsylvanian in age. Missouri coals are high-volatile bituminous in rank, ranging from C to A bituminous (Reference 2). Rank tends to decrease from older to younger beds, which probably relates primarily to the depth and time span of burial of the coals. The coalbeds follow a general northwesterly dip, deepening toward the center of the basin, which is in the western Missouri-Iowa border area. Much of the coal in Missouri is thin, averaging less than 2 feet.

Based on the coal deposit map of Missouri (Reference 2), Kansas City appears to be underlain by a major section of the coal-bearing strata, most of it being too deep to be economically mined. On the basis of the presence of favorable coalbeds. the potential for the occurrence of a coalbed methane resource in this area is reasonable. Rieke and others (Reference 21) list five primary criteria that they suggest should be used to evaluate the gas potential of coal seams in order to pick the best sites for resource development. These criteria are

1. Physical and chemical characteristics (rank)
2. Coalbed depth
3. Total effective coal thickness
4. Individual seam thickness
5. Areal extent

Of these five criteria, the first three are satisfied adequately at this site. The individual seams are not thick (2-foot average versus 5-foot recommended), and the areal extent is limited by the size of the facility.

No estimates of the methane content of these coals were found. The discussion of the Forest City Basin in the U.S. Department of Energy report *Methane Recovery From Coalbeds: A Potential Energy Source* (Reference 12), centers on the Iowa part of the basin only. Again, no estimates were made of the methane content, except in a general way that was included in a discussion of the CO_2 gas problems associated with the shallow mines (<300 feet deep) in south-central Iowa (Figure 6). This problem area may extend into Missouri, so if a more extensive evaluation of the methane potential of this site is made, close attention should be given to the coal gas quality.

MISSISSIPPI

The Air Station at Meridian, Mississippi, is situated in the middle of the Tertiary Mississippi-Alabama lignite trend (Figure 7). This lignite occurs in fluvial-deltaic to deltaic-shallow marine sediments of the Midway and Wilcox Groups and is Paleocene to lower Eocene in age. Individual lignite beds range up to 40 feet thick (Reference 20).

No information on the methane resource potential of these lignites was found but it is assumed to be low. The only gas determination for lignite that was found is in Diamond and Levine (Reference 22), in which they determined the total gas content for two samples from the Watkins E seam in Colorado to be 3.2 and 6.4 cf/T. Because lignite is the first step up from peat in the coalification process. its contained gas may also be expected to have a high CO_2 to CH_4 ratio (peat gas analysis showed 97% CO_2 and 3% CH_4), making the gas an undesirable energy resource.

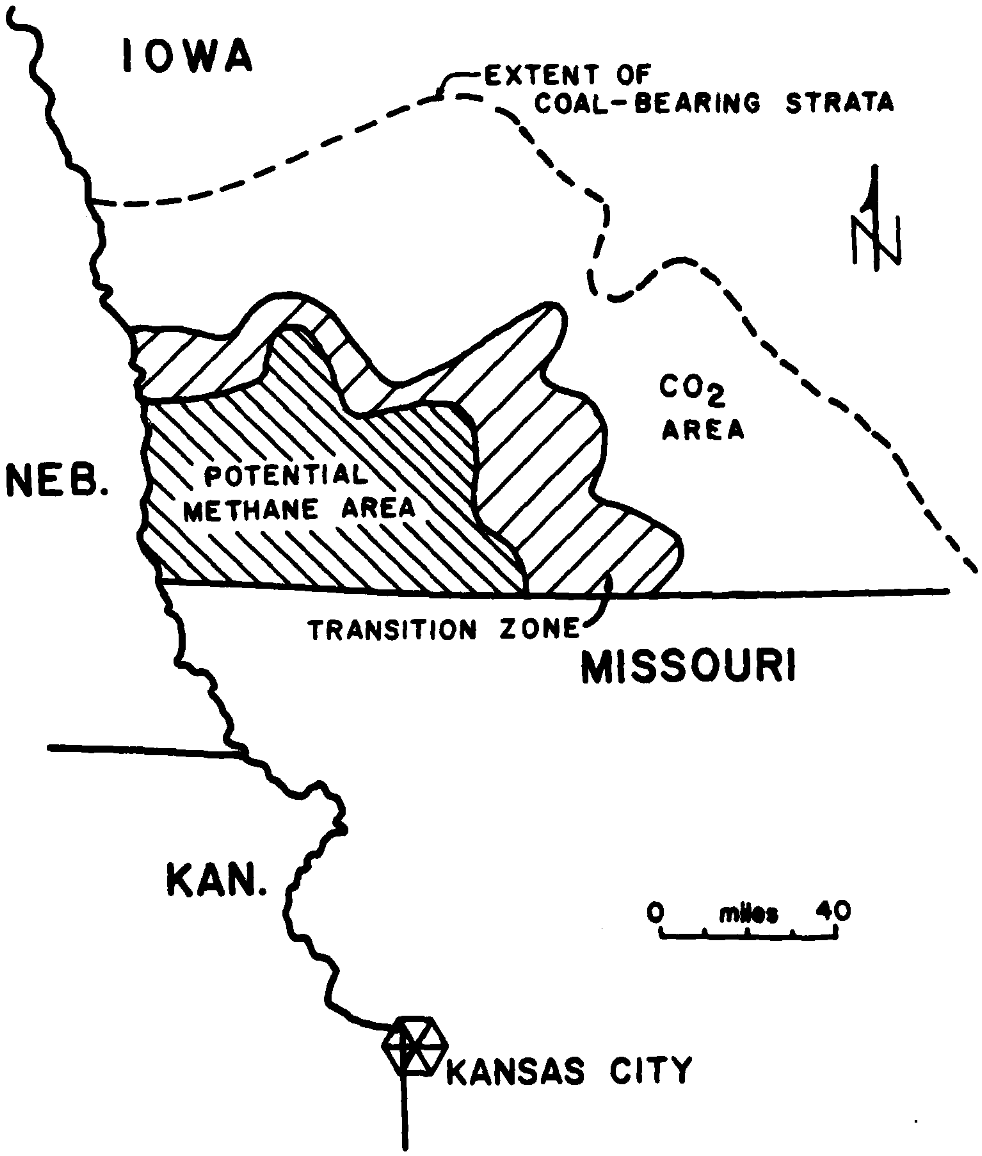

FIGURE 6. Map Showing the Area Estimated To Have Potential for the Occurrence of Methane or Other Coalbed Gas Associated With Deep Coals in Iowa. (*State boundaries do not limit the methane potential.*)

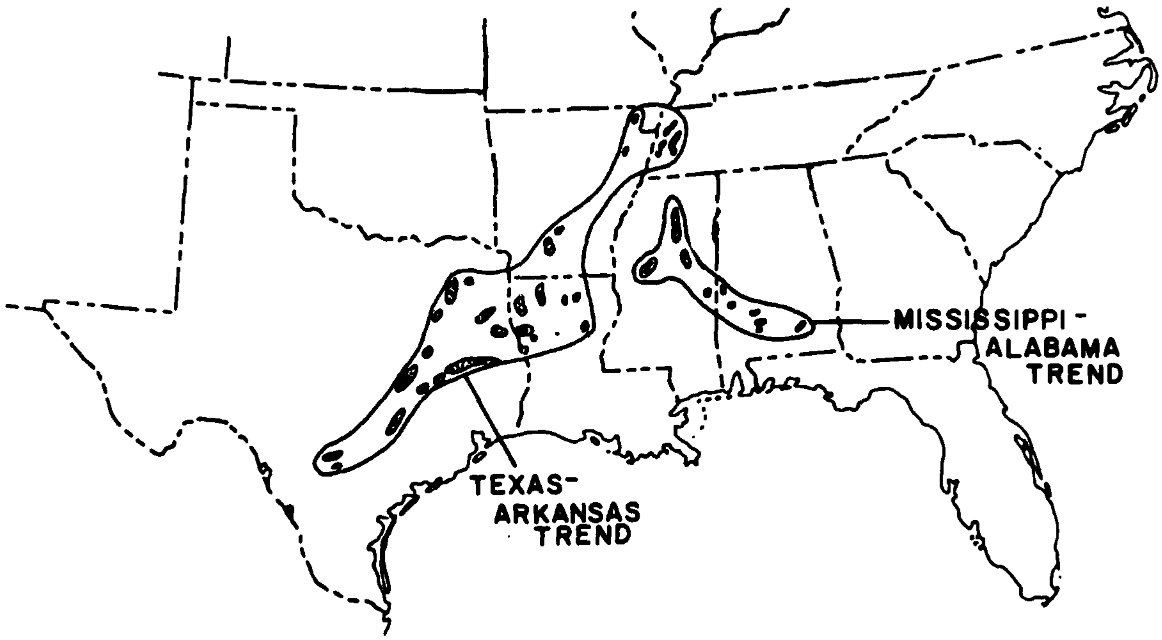

FIGURE 7. Trends of Lignite Occurrence in the Southern United States.

TENNESSEE

The coalbed methane potential for land beneath the naval facilities around Memphis is similar to that of the Meridian, Mississippi, area. The only coals that may occur in this area are lignites of the Texas-Arkansas trend (Figure 7). The *1984 Keystone Coal Industry Manual* (Reference 2) shows this area as possibly being underlain be deep lignites; but since the methane potential of lignites is low, the potential for a coalbed methane resource at any of these sites should be considered to be very low.

WASHINGTON

The coal-bearing sediments of western Washington were deposited in the early Tertiary on a broad, low-lying coastal plain that existed along the eastern shoreline of a north-trending outer-arc basin and interfingers with and grades into shallow marine sediments to the west. Knowledge of coal geology in the basin has been gained almost entirely from mining operations in the Cascade foothills and the Centralia-Chehalis area. The sedimentary rocks contain up to 20 coalbeds with thicknesses up to 40 feet for an individual bed (Reference 23). The entire sedimentary section has been structurally deformed by folding and faulting, which has been intense in many areas. In some places, at least five stages of deformation

have been mapped. This deformation is related to both east-west compression of the basin and formation of the Cascade volcanic-plutonic arc. The activity of the Cascade arc also resulted in a very high local thermal gradient that accelerated the metamorphism of the coals, resulting in a dramatic increase in coal rank (from west to east) from western Puget Sound and the Puget Lowlands through the foothills to the flanks of the Cascades. This metamorphic progression follows from subbituminous coals in the west to anthracites in the east. Much of the coal-bearing rock is covered by Pleistocene glacial till—in some places over 3000 feet thick.

Knowledge of the coalbed methane potential in the basin is limited and is based on methane-related mining accidents, water wells producing methane, and oil and gas exploration. The underground mines in many areas are known to be very gassy; and water wells in several areas in the Puget Lowlands produce methane, some in commercial quantities. These features could be the result of degassing of extremely fractured coalbeds. The gas content of western Washington coals has been assumed to range from 65 to 440 cf/T (Reference 18). Four coal core desorption tests from the Centralia-Chehalis district showed an average gas value desorbed of 47 cf/T for [illegible] subbituminous C rank coals, although a value of 50 cf/T is believed to be a reasonable minimum value for in-place subbituminous coal in the western Washington region.

All of the Navy facilities, except for the Radio Station at Oso, are west of the general north-south dividing line between bituminous and subbituminous coals, placing them in the subbituminous region. Oso is in the bituminous region of Snohomish County; but all of the Navy sites are outside the coal-mining regions, so little is known of their coal and coalbed methane potential. The Seattle site is in the secondary or "broad methane gas from coalbeds target" as defined by Choate and Johnson (Reference 23) for the Methane from Coalbeds Project (MCBP), which represents their most optimistic appraisal (based on available information) of areas likely to be underlain by producible coalbed methane resources in the western Washington region (Figure 8, modified from Reference 21).

The potential for coalbed methane resources at any or all of these sites is probably the best of any of the areas considered. There are, however, some important unknowns that must be addressed before any quantitative assessment can be made of the sites. Detailed subsurface geologic mapping of the coal-bearing units near the sites will help determine the actual location and rank of any coals underlying the sites. Several more core desorption and analysis tests are needed throughout the region before a true estimate of the expected gas content and gas quality can be made.

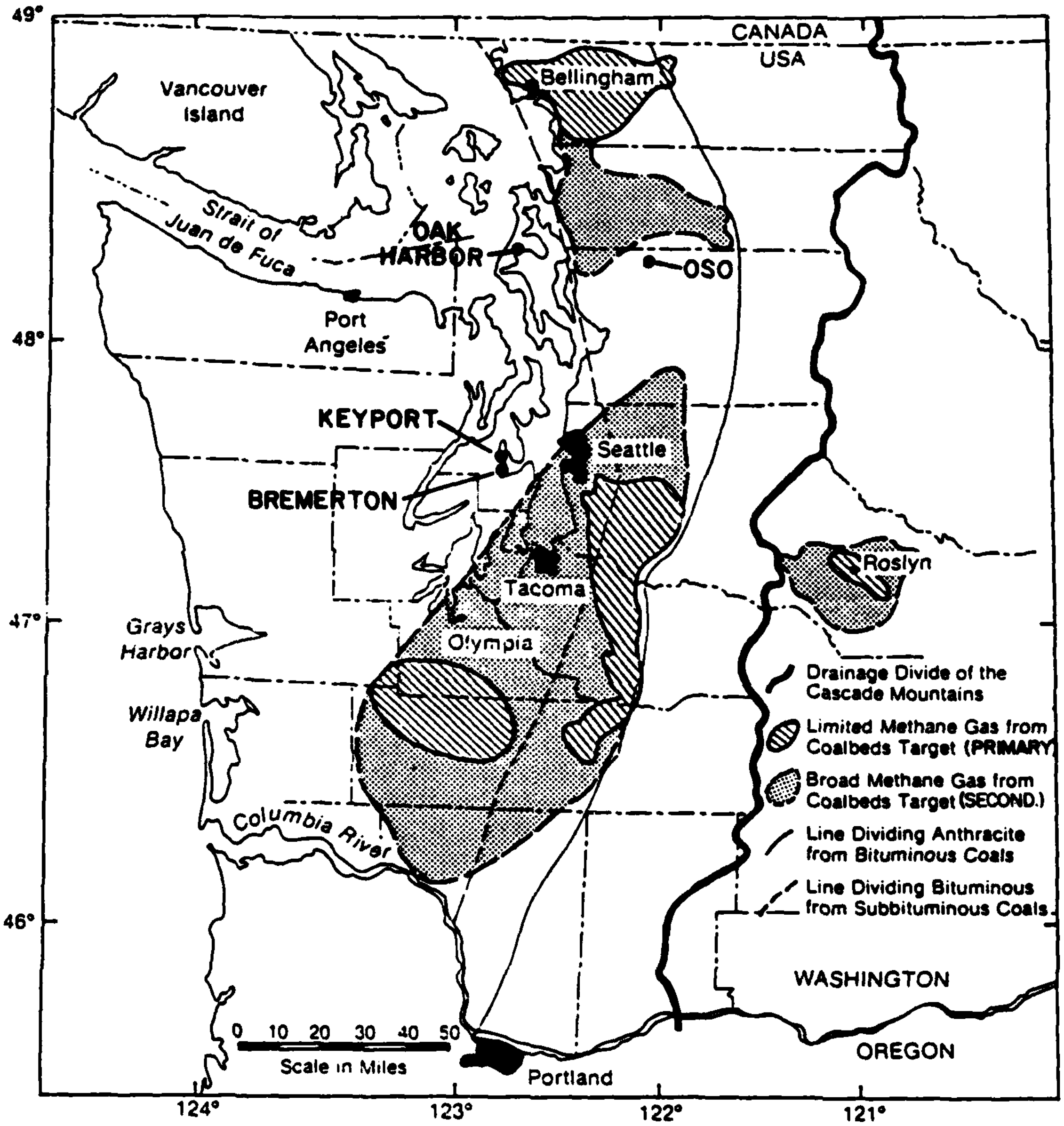

FIGURE 8. Areas of Coalbed Methane Potential in Western Washington.

OREGON

During the Tertiary Period the area under discussion was part of a marginal basin on the edge of the North American continent. Continental sediments deposited in this environment included the Eocene Coaledo Formation, which consists of approximately 6000 feet of sandstone, siltstone, and shale, with coalbeds occurring in the upper and lower portions of the formation. Lund makes reference to the mining of coal from this unit (Reference 24), and, based on a geologic map of the coast of southern Coos Bay County, Oregon, included in his paper, it appears that the Coos Head Facility is underlain by the coal-bearing formation. No indication of coal rank, coalbed characteristics, or methane potential was given and no other information came to light during the literature search.

CALIFORNIA

San Francisco Bay Area

A large part of the coalbed methane potential that exists in California (for the Navy) appears to be centered around the east side of San Francisco Bay. The area is underlain, in part, by fragments of Tertiary sediments that were deposited in a marginal basin. The Middle Eocene Domengine and Tesla Formations contain subbituminous coal that has been mined in relatively small quantities near Mt. Diablo in Contra Costa County and Corral Hollow in Alameda County east of San Francisco (Reference 25). In the late 1800s these mines supplied much of the domestic coal for San Francisco (Reference 26). A number of the coal mines east of San Francisco are reported to be very gassy (Reference 27), but no quantitative information on the methane content of the coals was found.

Because the San Francisco area has been very active, tectonically, since the deposition of the Tertiary sediments, the rocks have been fractured, faulted, displaced, and generally very badly jumbled to the point that it is difficult to project the surface exposures of the coal-bearing units into the subsurface beneath the naval facilities within the limits of this study. Of the Navy installations listed for this area, the Weapons Station at Concord and the Mare Island Shipyard at Vallejo are the only sites near which Tertiary rocks outcrop and may possibly be underlain by downdip extentions of them. The remaining sites at San Francisco, Oakland, and Alameda are in an area bounded by the San Andreas and Hayward Faults and the exposed rocks in this area are all older than the coal-bearing units. Large portions of the eastern bay area are covered by recent sediments, however, making it impossible to rule out the existence of subsurface coal-bearing units beneath this area without additional study.

The potential for coalbed methane resources in this area is difficult to assess because of the uncertainty that surrounds the subsurface occurrence of the coal-bearing units and the lack of quantitative data on the coals. Within the limits of this study, it can be said that the potential for several small occurrences of coalbed methane does appear to exist in the area. The resource will be limited by the low rank of the coal, the highly fractured and faulted nature of the rocks, and the shallowness of the occurrence.

Monterey Area

A second area of coalbed methane resource potential exists in Monterey County where the Miocene Temblor Formation contains minable high-volatile bituminous coalbeds. The coalbed averages between 14 and 15 feet in thickness at its outcrop (Reference 26). No methane data were found for these coals. The Temblor Formation outcrops south of Fort Ord in northern Monterey County, but no attempt has been made in this study to evaluate a subsurface occurrence of these rocks beneath the Postgraduate School area or to assess the methane potential of the coal. Speculatively, the potential may exist for resource at this site. The rank of the coal (and its expected gas content) and the thickness of the coalbed are favorable factors; the probable fractured nature of the rocks, their limited areal extent, and expected shallowness of the coalbeds are unfavorable factors relating to this potential.

RHODE ISLAND

Evaluation of the coalbed methane resource potential at the Davisville and Newport sites revolves around the Narragansett Coal Basin, which straddles the Rhode Island-Massachusetts boundary. Except for a short paragraph in the U.S. Department of Energy methane resource potential paper (Reference 12), no information on the basin was acquired. In that paper, the authors noted two previous works concerning the Narragansett Basin–one done at Boston College and the other at the University of Massachusetts (References 28 and 29). These papers and other information will need to be gathered before any evaluation of the coalbed methane resource potential of these sites can be made.

LEGAL/INSTITUTIONAL FACTORS

Two subjects must be addressed regarding coalbed methane resources on Navy lands: resource ownership and the disposition of the resource.

In the private sector, the question of legal ownership of the gas resource has been a major concern. There are two opposing points of view on this question. Some people, primarily in the coal-mining industry, believe that the gas belongs with the coal resource (which is classed as a mineral) and the rights to the use of the gas reside with the mineral owner. Historically, the coal mine operators were the only people interested in coalbed methane because of the hazards associated with its occurrence in the mines. Much of the industrial and governmental effort over the past 50 years has been aimed at increasing mine safety and efficiency by developing techniques to mitigate these hazards by ventilating the working areas to reduce the concentration of methane in the air and to degasify the coal ahead of the working face, through the use of both horizontal holes drilled in the working face and vertical holes drilled into the coal seam from the surface. Most of the gas was, and still is, vented to the atmosphere.

Over the last 10 years, interest has been building to use as much as possible of this wasted gas, either locally at the mine or by introducing it into pipelines for commercial distribution. Efforts have also been directed toward tapping methane resources in coals outside the present mine areas. Because of these efforts, others believe that this unconventional gas (unconventional in regard to its occurrence, not its chemical nature) should be considered the same as any other natural gas and that its use should fall under oil and gas regulations and its ownership should reside with the oil and gas leaseholder.

Litigation of this question is ongoing in some of the eastern coal-producing states on a case-by-case basis (References 30 and 31). It appears that while co-operation (between the coal miners and gas owners) is preferred, legislation to define ownership of the methane is thought to be necessary (Reference 31).

In most cases, Navy facilities are located on lands owned by the United States. These lands generally fall into one of two broad categories (Reference 32):

1. Public Domain Lands–lands acquired by the United States through treaty or purchase from another country and that have remained in federal ownership from the time they were acquired. These lands are withdrawn from the operation of public land laws and reserved for Navy and other military use.

2. Acquired lands–lands acquired from private owners by purchase, condemnation, donation, or other means.

In either case, where both the surface and mineral estates are owned by the U.S. Government, it is probably safe to say that the United States is also the owner of the coalbed methane resource.

Disposition of the resource on Navy lands depends upon whether the Navy has the authority to develop or authorize the development of coalbed methane on Navy lands. It is not clear if such authorization must be made by an express act of Congress. The Navy has been given the express authority to develop or authorize the development of other resources on Navy land.

The Military Construction Act of 1982 (10 USC s. 2689) gives the Secretary of the Navy the authority to develop, or authorize the development of, any geothermal energy resource within lands under his jurisdiction, including public lands, for the use or benefit of the U.S. Department of Defense. Similarly, the Naval Petroleum Reserves Act (10 USC s. 742) gives the Secretary of the Navy exclusive control over the lands inside the naval petroleum reserves.

In contrast, the Federal Land Policy and Management Act of 1976 (43 USC s. 1701 et seq) vests authority for the management of public lands, including public domain, acquired, and withdrawn lands in the Bureau of Land Management of the Department of the Interior. The Energy Policy and Conservation Act (42 USC s. 6201) creates a role for the Secretary of Energy and the President in the conservation of natural gas and the development of coal supplies.

43 CFR 3400 gives the Secretary of the Interior the authority to issue coal leases on all Federal lands with the exception of several categories of land including the naval petroleum reserves. Section 3400.3-2 states:

> The secretary may issue leases with the consent of the Secretary of Defense on acquired lands set apart for military or naval purposes only if the leases are issued to a governmental entity which:
>
> (a) Produces electrical energy for sale to the public;
>
> (b) Is located in the state in which the leased lands are located; and
>
> (c) Has production facilities in that state and will use the coal produced from the lease within that state.

In short, there are several groups interested in the development of coalbed methane resources on federal land. The resolution of the question of who has the authority to develop the resource will depend upon the particular nature of ownership of the land in question and legislation granting the authority to develop the resource. On Navy fee land it is likely that the Navy will develop the resource once it has authority to do so. On lands withdrawn for Navy use it is likely that the Bureau of Land Management will authorize the development subject to input from the Navy. In any case the potential for conflict among various federal factions could be great.

Another interest that must be considered is that of a particular state. For example, in the western states the public land surveys for each township reserve two sections (2 square miles) for schools. This land is clearly state controlled. Often when the state sells a school section it retains a one-sixteenth interest in any mineral resources associated with the land. If the Navy or other federal entity acquires a school section it must extinguish the state's interest in court. This is not always done, and indeed, the land may even be leased by the Federal Government as opposed to purchased. Thus, in each particular case the history and present status of land ownership must be determined to correctly assess potential claims to mineral ownership of school sections or former school sections.

Another area for potential conflict arises when coalbed methane is found in association with ground water in a closed basin or area where there are substantial appropriations of the water. In that regard, two issues arise:

. May the state require that the Federal Government obtain a permit prior to using such water on federal lands?

2. Will the link between the groundwater and the coalbed methane affect the Navy's ability to develop the resource on federal lands?

Case law apparently precludes the state from requiring a permit of the Federal Government conducting operations on federal lands.

A state's treatment of groundwater as being intimately linked to the coalbed methane should not mean that the Navy must comply with state water law regarding exploitation of the resource without a demonstrated relationship between the coalbed methane and an appropriated water supply. Once such a relationship has been established, the issue will become the purpose of the Congressional reservation and the extent of the implied reservation of water necessary to carry out that purpose. In short, state water law should not determine the relative rights of water users as regards the use of water on federal lands. When the United States reserves land for a purpose, by implication it reserves enough unappropriated water to carry out that purpose, which is superior to the rights of future appropriators. Thus, the Federal Government need not go through state procedural requirements to perfect a water right. That right is automatically perfected at the time of the reservation.

The ability of a state to regulate Navy activities on federal land is limited by the doctrine of federal preemption rooted in the Property (Art. IV, s. 3, cl. 2), Supremacy (Art. IV, s. 3, cl. 2), and Necessary and Proper (Art. I, s. 8, cl. 18) clauses of the United States Constitution. Under the concept the states have only the authority to regulate federal activities that is expressly granted by a clear statement of Congressional intent found in the legislation and regulations authorizing the activities sought to be regulated. An analysis of the states' authority to regulate

such activity must therefore begin with the legislation and regulations that allow coalbed methane activities on federal land and the case law. This legislation will determine the extent of state control.

To reiterate, the area of central concern to the resolution of all of the issues associated with the development of coalbed methane is that of the definition of the resource as part of the coal, oil, or gas rights. The resolution of this issue will determine ownership of the resource as well as which laws are applicable to its development.

OTHER FACTORS

This report is limited by time and available information; therefore, it has concentrated on the regional geologic environment of each site. It does not address anything of a non-geologic, site-specific nature. Facility size, energy requirements, present energy source, adaptability of this energy source to the facility needs, and the like are not addressed. Because of the marked lack of coalbed-methane-related production data, balancing the facility energy requirements with a minimum resource size, or evaluating the cost of developing and producing this resource as opposed to the present energy source or another alternative source was not possible. The lack of coalbed-methane-related data is of prime concern to anyone considering involvement in the resource.

Two good, but possibly dated, reviews of the state of coalbed methane resource development are the 1978 Department of Energy report on a commercialization strategy for the recovery of natural gas from unconventional sources, by Ham and others, (Reference 33); and the 1980 Noyes Data Corp. review of unconventional natural gas in general, edited by Satriana (Reference 34). In addition to a discussion of the state of coalbed methane technology development, these reports also include several economic scenarios for coalbed methane production.

With regard to technological development, a number of the geologic and non-geologic factors that affect the producibility of the coalbed methane resource were noted. Geologically, the principal uncertainties center on the gas content and quality, and the gas productivity of coal seams, especially outside the eastern mining areas. Such uncertainty also applies to the deeper coals in all areas. Because of the high cost of deep drilling and well testing, little is known of the methane potential in thick coal beds that occur at depths of more than 3000 feet.

The non-geologic factors have to do mainly with environmental and economic concerns. Both Ham and Satriana assessed the environmental readiness of this resource. They believe that coalbed methane can be commercialized, given available environmental safeguards and monitoring, with limited additional environmental research.

These environmental concerns relate primarily to waste-water disposal because most of the coalbed methane tests to date have shown that some dewatering of the coalbed is necessary to stimulate methane desorption and removal.

The conclusions drawn from both of these sources is that future production from both minable and unminable coalbeds is dependent on additional research and development, although some recovery methods are presently technically feasible and potentially cost effective. The most often cited near-term application of profitable coalbed methane recovery is in conjunction with mining operations where the methane removal costs can be written off as mine health and safety measures. In this context, the technology is relatively simple and available, and is in fact, commonly used in several European countries, notably Great Britain and Belgium. To the best of our knowledge, this application is not an option at any Navy facility.

An economic evaluation of each site will be necessary, of course, but it is the consensus of these two studies that in view of the limited experience in using coalbed methane and the experimental nature of its production, the cost of developing the resource and the ultimate cost to the consumer cannot be established with certainty at this time. The economics of coalbed methane utilization will need to be approached on a case-by-case basis to gain operative and cost experience.

CONCLUSIONS

This paper was designed to address the question, "Does the potential for a coalbed methane resource exist at any Naval Shore Facilities in the United States?" The answer to this question is that yes, a limited potential does appear to exist at several facilities, all in the continental United States. However, based on the assessment criteria (and the conclusions) developed here and by the work of several major coalbed methane exploration efforts (References 12, 17, and 21) primarily associated with the Department of Energy Methane Recovery from Coalbeds Project, no U.S. Navy facility is located in a primary target area for the development of a coalbed methane resource in the United States.

The potential of each site identified is limited by one or more of a variety of factors that include low coal rank, shallow or near outcrop occurrence, thin individual seams, excessively fractured ground, questionable gas quality, and simply a lack of coalbed-methane-related data.

Because this report is primarily a search of coalbed methane literature, little site-specific information was made available; and indeed, because of the newness of the industry, little information may exist. This is particularly true for non-mining

areas and minor coal occurrences. It is also true for the subject of gas quality and quantity because these can be determined only by drill core analysis, which has not been done in many areas.

If the Navy wishes to pursue further the potential of this alternative energy source, a site-by-site evaluation strategy is recommended. The following is a proposal for the evaluation of a single site (the Bremerton, Washington, facilities) with a positive outcome. In it are critical evaluation points (CEP) at which project direction decisions will need to be made.

This site-evaluation scheme is based on the premise of on-site use of the resource rather than the development of the resource as pipeline feed for distribution to other facilities.

The first step in the strategy is two-fold: to identify the applicability of a coalbed methane (CBM) resource at the site, and to determine who owns the CBM resource.

The Bremerton facilities include the Regional Medical Center, the Puget Sound Shipyard and Supply Center, and the Submarine Base, Bangor. The fuel consumption at these facilities is undoubtedly great and includes mobile fuels and fuels for space heating, steam boiler feed, and standby electricity generation. Can these present fuel supplies be augmented or replaced by CBM if it was available, and what would be the conversion costs (equipment retrofit, and the like)? What are the benefits of an on-site, uninterruptable natural gas source as opposed to the present sources? Would there be environmental benefits, such as fewer pollutants? Addressing these and related questions will lead to an assignment of both need and applicability of a CBM resource.

The question of legal ownership of the coalbed-methane resource will be answered at this stage as well. As noted earlier in the Legal/Institutional Factors section, the resource classification of CBM is still uncertain because of the conflicting views of the coal mining industry and oil and gas interests. This conflict must be clarified before the Navy invests much effort in a resource evaluation.

CEP No. 1

If a coalbed-methane resource exists beneath the Bremerton facilities, does the Navy own it and does the Navy have a use for it?

The next step is to incorporate all available data on the geology of the site into the coalbed-methane-occurrence model developed in this paper for the western Washington region. Sources of data will include previous coal and coalbed-methane

studies done in other parts of western Washington, local coal-mining records, old logs and production records from water wells both at the facilities and in the surrounding area, and oil and gas exploration well logs, geophysical surveys, and remote sensing surveys made throughout the Puget Sound region.

Based on the known geology and data on the land holdings of the facilities, make an estimate of the "blue-sky," in-the-ground, coalbed-methane resources. This estimate will reflect the magnitude of the resource that might exist and will give no indication of recovery percentages or production costs. Because of the lack of data on both coalbed-gas quantity and quality in the Northwest, the accuracy * of this estimate will be on the order of plus or minus 100%.

It is now necessary to conduct a preliminary sensitivity study on this resource estimate. Some of the factors that will be considered are exploration and development costs, production and recovery estimates, production costs, environment-related costs, and the cost of equipment retrofit. Exploration and development costs are primarily related to geophysical surveying, drilling, well logging, sample analysis, and well completion. Production costs revolve around well drilling and completion, formation stimulation or treatment, and well-head gas collection, processing, and distribution. Also important to this study is the cost of the fuel that the CBM is meant to replace. As with many of the geologic factors, several economic factors are only poorly defined, particularly those relating to gas production and recovery. All production and recovery data available are for projects in New Mexico, Alabama, and West Virginia and cannot be used in western Washington as direct estimates. These former projects are being pursued in prime CBM target areas with thick coalbeds of moderately high rank and known gas concentration and quality, which is a situation very different from that with which the Navy is faced in the Puget Sound area. Because of these factors, confidence limits on the resource estimate will continue to be broad.

CEP No. 2

Based on the conclusions of a sensitivity analysis of the blue-sky resources, does the resource potential justify continued effort?

Up to this point all work was done on paper. It is now necessary to assess the gaps that exist in the geologic and economic data and how they can be filled so that a true geologic resource (and possibly an economic reserve) can be established. First stage field work will consist of the following as deemed needed: geologic

* Accuracy in the case of mineral resource evaluation is defined as the generally accepted confidence limits for the resource category of interest. The confidence limit for the best defined economic reserve is normally plus or minus 20%.

mapping, water well sampling (for dissolved gasses), and geophysical surveying (surface seismic lines, relogging old wells specifically for coal and coalbed gas intercepts). Based on the results of the field work, sites will be selected for exploration holes and production test wells. (No data were found during the present study indicating the depth to the coal-bearing formations beneath the Bremerton area; but based on the geology of the coal-mining areas east of Puget Sound, it is reasonable to assume depths of 1000 to 5000 feet.)

The exploration holes will serve several purposes, first among which will be to test for the actual existence of coal beneath the Bremerton facilities. With core samples of the coal we will be able to determine both gas quantity and quality and to conduct desorption tests to gage possible production rates. With geologic and geophysical well logging techniques, we can achieve a better characterization of the subsurface geology and many of the factors affecting the occurrence, quantity, and producibility of CBM at this site. Some of these factors are coal rank and quality; and lithologic variation of the surrounding rocks, faults, and fracture zones.

Some of the exploration holes may be completed as production test wells so that flow tests can be run and actual production estimates can be made.

The number of holes that will be drilled will depend on the geologic model established earlier, so the number may change as this model is modified with the new data. More data points (drill holes) are required to accurately define small, discontinuous coalbeds than to define thicker, more continuous coalbeds. To define the coal and coalbed-gas characteristics in the Bremerton area will require only a few holes. It is not unreasonable to assume, however, that more holes will be needed to define the continuity of the coalbeds and the producibility of the gas.

CEP No. 3

Conduct a second sensitivity study on the updated resource evaluation. Does a viable resource exist and can it be economically produced at this time?

The final step will be to enter the production phase. This phase will include formation of production wells by completing exploration wells and drilling new wells; construction of a surface gas-processing plant, if necessary; and construction of a gas collection/distribution system, retrofit of existing equipment, if necessary, and creation of a production and maintenance organization.

There can be, of course, innumerable convolutions to any resource evaluation strategy, many of them dependent on factors such as legal and contract issues, permitting requirements, and partial successes in the exploration phase. The strategy outlined above is intended to show the magnitude of effort involved in a site evaluation without getting bogged down in a myriad of details.

As stated, a limited potential does appear to exist at several Navy sites. However, assessing that potential, determining the quality of the resource and the applicability of the resource to the individual facility, as well as answering the questions of resource ownership and resource disposition, will take a great deal more effort.

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